Thermal performance of a flexible polypropylene pulsating heat pipe at different bending angles

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Abstract. The thermal performance of flexible polypropylene pulsating heat pipes (PHPs) is characterized for different spatial orientations, different reciprocal positions of the evaporator and the condenser (configurations), and different bending angles (conformations). The dependence of PHPs performance on their geometric orientation, configuration and conformation is poorly understood to date, however it is essential to develop polymeric PHPs characterized by high mechanical flexibility, which will have significant impact on thermal management of smartphones, portable electronics, and deployable systems such as cube satellites. Prototype PHPs were fabricated bonding together three polypropylene sheets by selective transmission laser welding, after cutting out a serpentine channel in the central sheet. The thermal performance of the devices was characterized by supplying an ascending/descending stepped thermal power ramp to the evaporator, and measuring the corresponding equivalent thermal resistance between the evaporator and the condenser.

1. Introduction

Pulsating heat pipes (PHPs) have been widely investigated in the last decade, especially for space applications [1], for their ability to work under different orientation without assistance from gravity for the return of the condensate to the evaporation zone. Whilst the metallic structure of the PHP allows optimal thermal performance, the stiffness of the structure limits the application to rigid devices. This often prevents potential applications to a range of novel consumer technologies, where mechanical flexibility, weight and cost are critical constraints. The development of polymeric PHPs charachterised by high mechanical flexibility will have significant impact on thermal management of smartphones, portable electronics, and deployable systems such as cube satellites.

The first attempts at fabricating hybrid PHPs consisting of copper tubes and Teflon joints did not guarantee long-term gas tightness, which has been identified as one of the critical limitation of polymer materials in two-phase passive devices [2]. The mitigation of gas diffusion through the polymer sheet can be achieved with the insertion of thin metallic layers [3]. Recently, a flexible pulsating heat pipe was fabricated by thermal sintering a multilayer polymer film including an aluminum layer acting as gas

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barrier on the two sides of a low-density polyethylene sheet cut into a closed-loop PHP shape [4]. To minimize the leakage of non-condensable gases, the heat pipe edge was sealed with an indium coating. An alternative approach to fabricate a flat plate fully polymeric PHP consists in embedding the PHP serpentine channel into a composite polypropylene sheet [5,6]. In particular, the serpentine channel of the PHP is cut-out in a black polypropylene sheet, which is in turn sandwiched between two transparent sheets of the same material and bonded together by selective transmission laser welding [7,8]. Due to the small thickness of the polymer sheet, the PHP channel has a large aspect ratio, resulting into so-called "pulsating heat stripes" (PHS), which can be seen in practice as an engineered composite polymer sheet with enhanced thermal conductivity [9].

Because the development of polymeric pulsating heat pipes is still in its infancy, to date there is no systematic assessment of the effect of orientation, configuration and conformation parameters on their performance. The PHP spatial orientation affects in a complex way its thermohydraulic behaviour. In particular, the inclination with respect to gravity and the reciprocal position of the evaporator and the condenser (i.e., the PHP configuration) have rather intricate and poorly understood effects on the PHP performance [10]. In the case of flexible PHPs, an additional geometric parameter to consider is the PHP conformation, i.e., any of the spatial arrangements the PHP may adopt by bending or folding at one or more points. To partially address this gap in the current understanding of flexible pulsating heat pipes, the present work reports the results of an experimental investigation of the effects of geometric parameters on the thermal performance of a flat polypropylene pulsating heat pipe fabricated by selective transmission laser welding.

2. Materials and methods

2.1. PHP Design and manufacturing

The most important design parameters of a pulsating heat pipe are the hydraulic diameter, which for a rectangular channel is $D_H = 2Wt/(W + t)$, where W is the channel width and t its height, and the number of turns of the serpentine channel. In the present work, the study is limited to a three-turns channel.

The hydraulic diameter was determined based on the Bond number, defined as:

$$Bo = \frac{g(\rho_L - \rho_V)D_H^2}{\gamma \cos\theta} \tag{1}$$

where g is gravity, ρ_L and ρ_V are, respectively, the liquid and the vapour densities, σ is the surface tension, and θ is the equilibrium contact angle of the heat transfer fluid on polypropylene. Here, the fluid used was ethanol, which has a very high wettability on polypropylene surfaces ($\cos\theta \approx 1$) [10]. To ensure the fluid circulation is driven by capillary forces instead of buoyancy, one must set an upper limit to the Bond number ($Bo < 4$) [11,12]. There is also experimental evidence of a lower limit for PHP operation, $Bo > 0.4$ [13]. Accordingly, the range of acceptable hydraulic diameters for PHP operation becomes:

$$0.63\sqrt{\frac{\gamma \cos\theta}{g(\rho_L - \rho_V)}} < D_H < 2\sqrt{\frac{\gamma \cos\theta}{g(\rho_L - \rho_V)}} \tag{2}$$

Using ethanol as heat transfer fluid, equation (2) suggests the Bond number falls within the range suitable to PHP operation for channel widths between 2.5 and 10 mm. However, there is an additional constraint on the channel width due to the relatively low elastic modulus of polypropylene. If the channel width is large, the thin (0.4 mm) polypropylene wall changes its shape according to the pressure difference between the heat transfer fluid and the atmosphere. This affects both the pressure level during operation and the hydraulic diameter, as shown by preliminary experiments conducted on a polypropylene PHP having a channel width of 9 mm [6]. In conclusion, a channel width $W = 5$ mm was selected to meet all of the above constraints, corresponding to a hydraulic diameter $D_H = 1.23$ mm.

The pulsating heat pipe studied in the present work was built using rectangular polypropylene sheets (average thermal conductivity: 0.16 W/mK) with a length of 250 mm and a width of 100 mm. The serpentine channel was cut-out in a black polypropylene sheet (0.7 mm thickness) using a commercial laser cutter (HPC Laser LS1290 Pro). Then, the channel was sandwiched between two transparent sheets (0.4 mm thickness each), which were bonded to the black sheet by selective transmission laser welding using a nanosecond pulsed fibre laser (SPI Lasers G4 HS-L 20 W) [5,6,9,10]. The resulting composite polypropylene sheet, displayed in figure 1, had an overall thickness of 1.5 mm. The cutting quality depends on many parameters such as the kerf width, the cut edge roughness, the dross and the width of the heat affected zone (HAZ). However, the most critical parameter is the kerf width, which must be as small as possible. To improve the cut edge finish, cutting should be carried out repeating several engraving passes, removing approximately 0.1 mm of material at each pass. After cutting, any debris, dross and dirt that may affect the weld quality were removed from the cut edge.

Figure 1. PHP design with a 3-turns, 5 mm width channel.

2.2. Experimental setup

The schematic layout of the experimental setup is shown in figure 2. The flat polypropylene PHPs were clamped on a hinged support frame, which could be inclined between -90° and 90° with respect to the vertical, and bent in the centre between -180° and 180° with respect to the straight conformation. Inclination angles were set with the aid of two digital goniometers fixed to the support frame. The heat supply was provided to both sides of the evaporator by two ceramic heaters (100 W each); two copper plates were used to distribute heat uniformly. The heaters were connected to a regulated DC power supply (Circuit Specialists CSI 12001X) to enable a fine control of the power input (instrumental accuracy: ±2.2%), while four fan-assisted heat sinks were used to remove heat from the condenser section. The evaporator and the condenser sections had an identical length of 4 cm.

The PHP was connected to a pressure transducer (Gems 3500, 0–160 kPa, instrumental accuracy: ±0.4 kPa) and to a micro-metering valve used in turn to vacuum the PHP and to fill the PHP with the heat transfer fluid. The pressure transducer DC output was sampled at 1 Hz by a data acquisition system (LabJack U6). Eight surface thermocouples (Omega Engineering) with response time $\leqslant$0.3 s and flat probe junction (instrumental accuracy: 0.75%) were securely fastened between the PHP surface and the clamps, four in the evaporator zone and four in the condenser zone, and connected to a data acquisition system. The temperature distribution in the adiabatic region was monitored by a FLIR infrared camera (Hti-Xintai A1).

2.3. Experimental procedure

The heat transfer fluid used in experiments (ethanol) was de-gassed in a vacuum chamber (Bacoeng) for 24 h before use. To introduce the heat transfer fluid, the PHP was vacuumed to a pressure of 0.5 ± 0.1 kPa (abs) using a two-stage vacuum pump (Bacoeng); then, the fluid contained in an external syringe reservoir was slowly driven by the atmospheric pressure into the PHP as the micro-metering valve was gently opened. The filling ratio was 50% of the total PHP volume (1.5 mL).

The PHP was mounted on the support frame in a configuration with the evaporator at the bottom and the condenser at the top. Tests were carried out for four different conformations of the PHP: (i) evaporator inclined at 45° and vertical condenser; (ii) horizontal evaporator and vertical condenser; (iii) vertical evaporator and condenser inclined at 45°; (iv) vertical evaporator and horizontal condenser. Each test was carried out using a fresh PHP unit to ensure uniform experimental conditions.

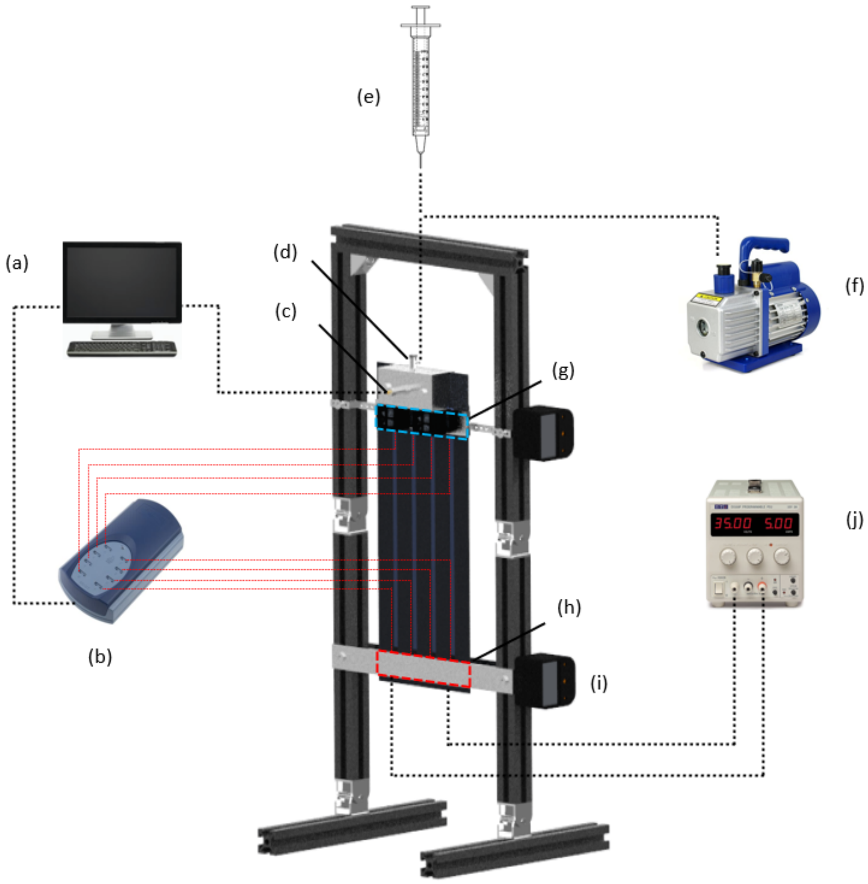

Figure 2. Layout of the experimental setup. (a) data acquisition system; (b) temperature data logger; (c) filling valve; (d) pressure sensor; (e) filling syringe; (f) vacuum pump; (g) condenser heat sinks; (h) electric heaters; (i) inclination meters; (j) power supply.

In order to characterize the start-up heat flux, a first series of experiments was carried out by applying a constant heating power supply to the evaporator section of the PHP, starting from a power of 4 W, and measuring the temperatures on the PHP surface at a sampling rate of 1 Hz. After each test, the system was cooled down to ambient temperature before repeating the test, with an increased heating power in steps of 2 W.

To evaluate the PHP performance, a second series of experiments was conducted by applying to the evaporator section an ascending/descending stepped power ramp ranging between the startup value and 25 W, and measuring the temperatures on the PHP surface at a sampling rate of 1 Hz. For each power step, the heat supply was kept constant until a pseudo steady-state regime was attained, which typically required 60 minutes. Tests were interrupted earlier in case any point of the PHP reached a temperature of 120°C, to avoid polypropylene softening and/or melting.

The equivalent thermal resistance was calculated as:

$$R = \frac{T_{ev} - T_{cond}}{\dot{Q}} \tag{3}$$

where T_{ev} and T_{cond} are the averages of the four temperature measurements of the PHP surface at the evaporator and the condenser, respectively, in the pseudo steady-states corresponding to each level of the power input, $\dot{Q}$.

3. Results

3.1. PHP start-up

The analysis of the unstable behaviour of the PHP for low heat inputs is used to determine the magnitude of the start-up heat input. In conventional PHPs built with metallic materials, for low initial heat input levels the behaviour is mainly unstable and cannot reach a pseudo-steady-state even if the heat input is increased during the experiments; for higher initial heat input levels the behaviour is much more stable and a pseudo-steady-state regime can be reached at each higher heat input level thereafter. Since the thermal conductivity of polypropylene is very small compared to metallic materials, the PHP used in the present study has a relatively slow response to a step power input hence a smoother transfer of energy to the fluid. As a consequence, the strongly unstable behaviour characteristic of low heat input magnitudes is not observed, and the PHP always attains a pseudo-steady-state regime.

The onset of the heat transfer fluid oscillation/circulation, corresponding to the PHP start-up, is marked by an abrupt, small amplitude decrease of the PHP surface temperature, followed by temperature and pressure fluctuations. This is shown in figures 3-6, for the four different conformations of the PHP considered in the present work.

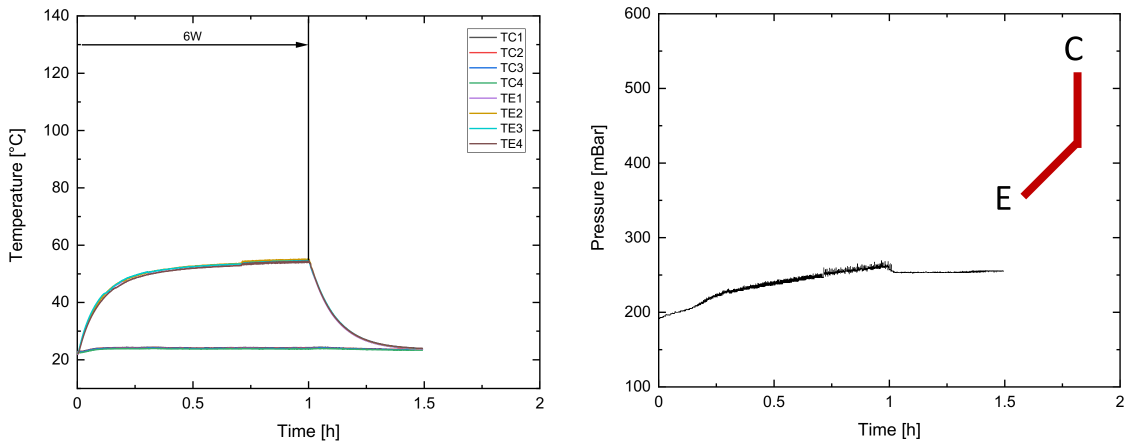

Figure 3. Temperature (left panel) and pressure (right panel) response to a constant heating power supply of a PHP with evaporator inclined at 45° and vertical condenser.

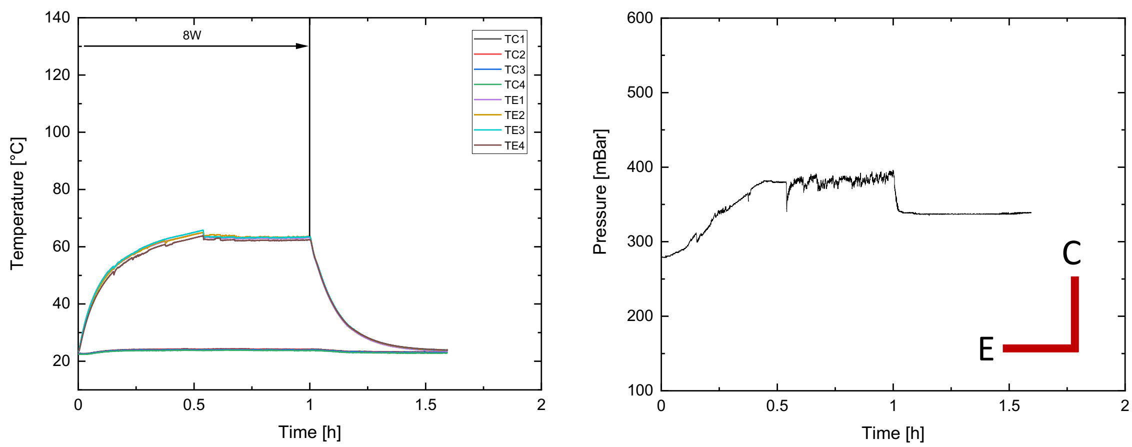

Figure 4. Temperature (left panel) and pressure (right panel) response to a constant heating power supply of a PHP with horizontal evaporator and vertical condenser.

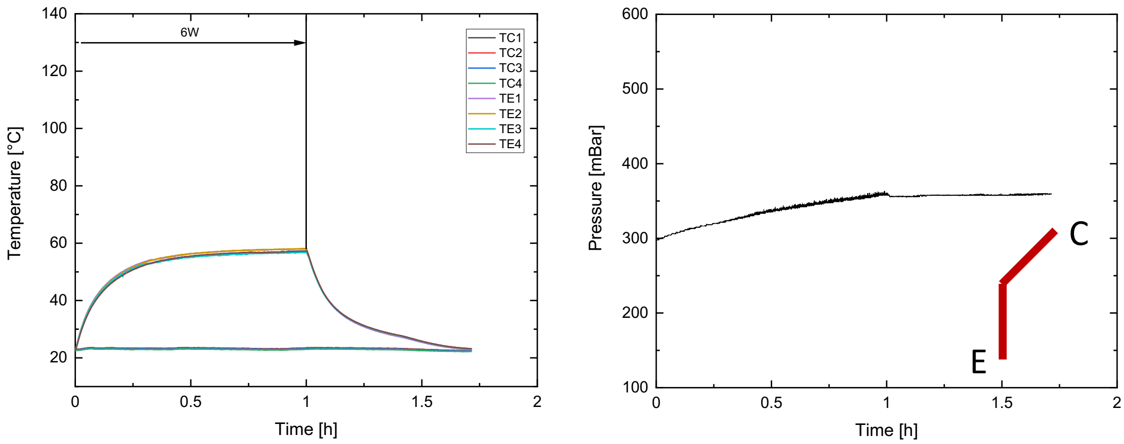

Figure 5. Temperature (left panel) and pressure (right panel) response to a constant heating power supply of a PHP with vertical evaporator and condenser inclined at 45°.

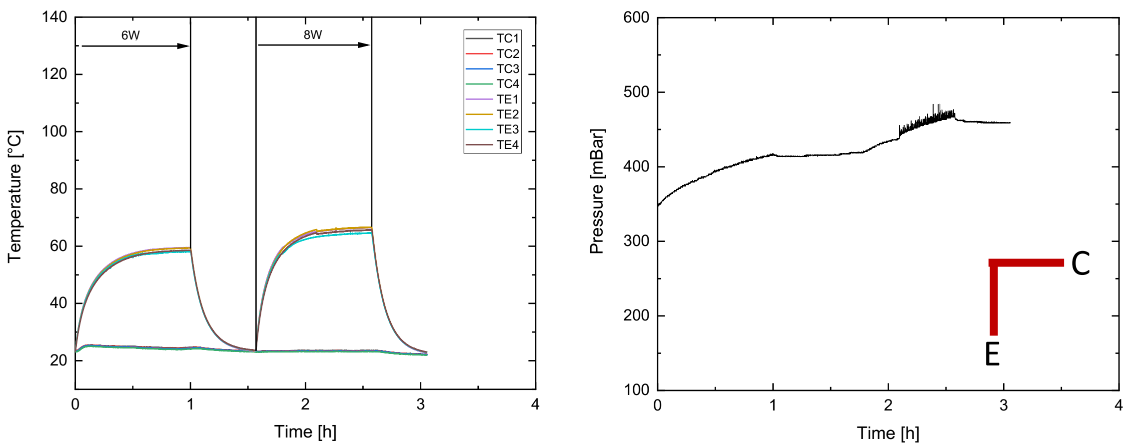

Figure 6. Temperature (left panel) and pressure (right panel) response to a constant heating power supply of a PHP with vertical evaporator and horizontal condenser.

For the smaller bending angle of 45° (figures 3 and 5), the pressure and temperature fluctuations characteristic of the PHP start-up are observed at a heat input of 6 W, while for the larger bending angle of 90° (figures 4 and 6) the input level required for the PHP start-up is 8 W. This indicates that increasing the bending angle has an adverse effect on the onset of the fluid circulation, and consequently increases the start-up heating power.

3.2. PHP performance

The thermal performance of the PHP achieved in the four different conformations considered in the present work was estimated based on the values of the equivalent thermal resistance, defined by Eq. (3), and is summarised in figures 7-10, which show the temperatures measured in the evaporator and in the condenser zones of the 3-turns PHP during the ascending/descending heat supply ramp, along with the corresponding values of the equivalent thermal resistance.

In all conformations, the PHP attains an asymptotic value of the minimum thermal resistance around 4 °C/W, which is approximately one third of the equivalent thermal resistance of the composite polypropylene sheet without heat transfer fluid (about 11 °C/W). Thus, the value of the minimum thermal resistance is consistent with that measured for the same 3-turns PHP in straight conformation

[10]. However, in conformations with smaller bending angle (45°, figures 7 and 9), the maximum heat input is about 25W, i.e. 25% higher than the maximum heat input of the PHP bent at 90° (20W).

These results suggest the PHP conformation, characterised by the bending angle and the mutual orientation of the evaporator and condenser sections, does not affect significantly the thermal performance expressed in terms of the equivalent thermal resistance of the PHP.

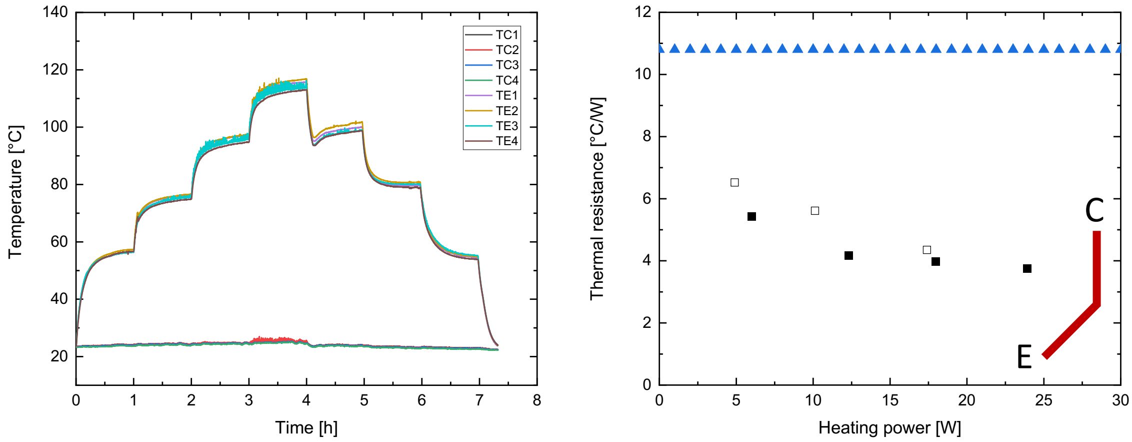

Figure 7. Response to an ascending/descending heating power ramp (left panel) and corresponding equivalent thermal resistance (right panel) of a PHP with evaporator inclined at 45° and vertical condenser. Heat input levels: 6.2 W, 12.2 W, 17.96 W, 23.9W (ascending), 17.4 W, 10.12 W, 4.87 W (descending). Filled and open squares correspond to increasing and decreasing heating power, respectively. Triangles indicate the thermal resistance of the polypropylene PHP without heat transfer fluid.

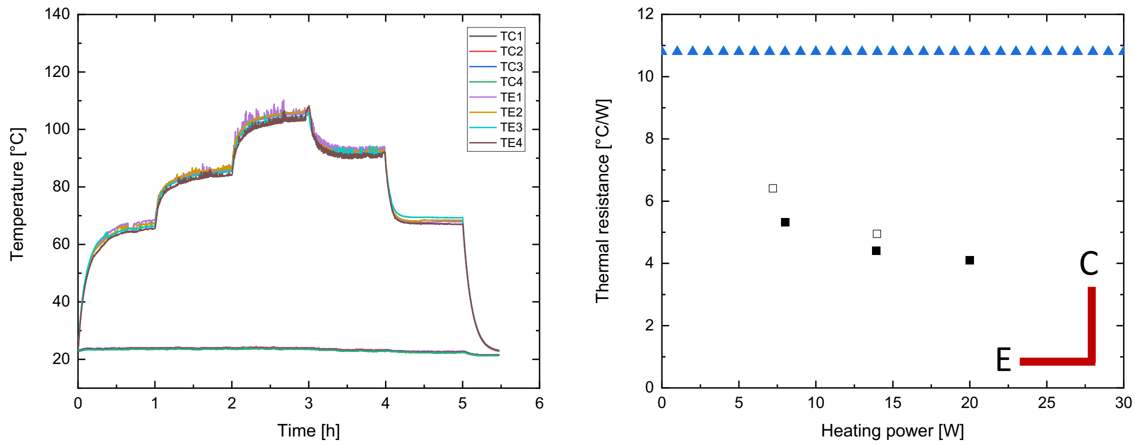

Figure 8. Response to an ascending/descending heating power ramp (left panel) and corresponding equivalent thermal resistance (right panel) of a PHP with horizontal evaporator and vertical condenser. Heat input levels: 8 W, 13.9 W, 19.97 W (ascending), 13.96 W, 7 W (descending). Filled and open squares correspond to increasing and decreasing heating power, respectively. Triangles indicate the thermal resistance of the polypropylene PHP without heat transfer fluid.

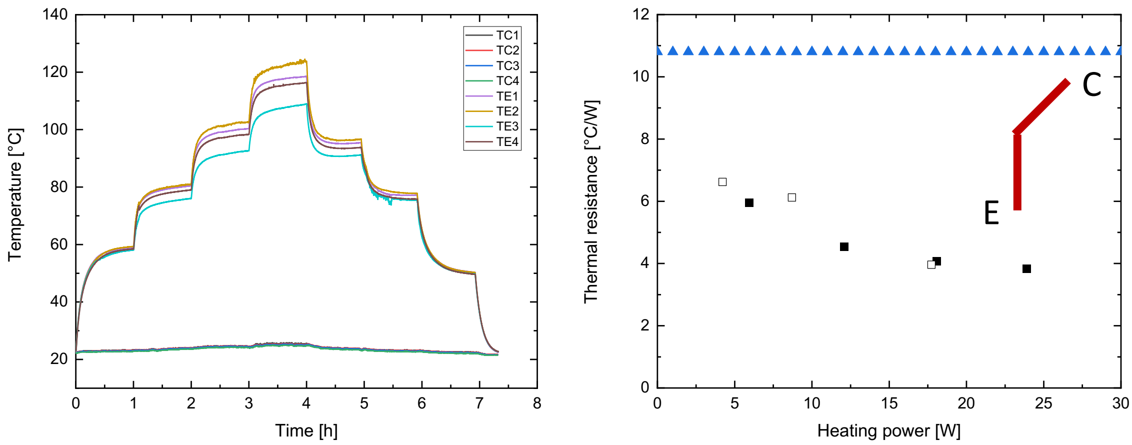

Figure 9. Response to an ascending/descending heating power ramp (left panel) and corresponding equivalent thermal resistance (right panel) of a PHP with vertical evaporator and condenser inclined at 45°. Heat input levels: 5.98 W, 12 W, 18 W, 24 W (ascending), 17.73 W, 9 W, 4.24 W (descending). Filled and open squares correspond to increasing and decreasing heating power, respectively. Triangles indicate the thermal resistance of the polypropylene PHP without heat transfer fluid.

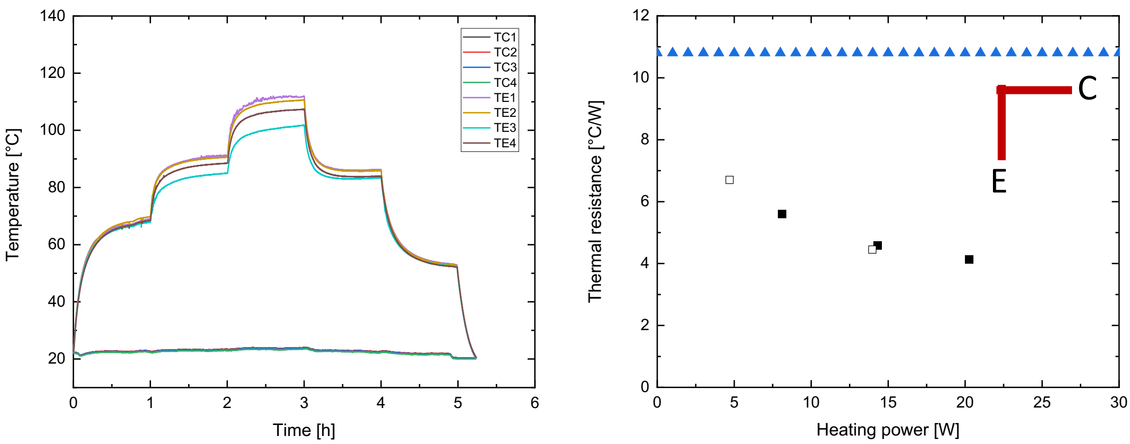

Figure 10. Response to an ascending/descending heating power ramp (left panel) and corresponding equivalent thermal resistance (right panel) of a PHP with vertical evaporator and horizontal condenser. Heat input levels: 6 W, 14.2 W, 20.2 W (ascending), 14 W, 4.7 W (descending). Filled and open squares correspond to increasing and decreasing heating power, respectively. Triangles indicate the thermal resistance of the polypropylene PHP without heat transfer fluid.

4. Conclusions

The thermal performance of a flat polypropylene pulsating heat pipe with a three turns channel fabricated by selective transmission laser welding and using ethanol as heat transfer fluid was investigated experimentally to investigate the effects of the PHP conformation. Specifically, four different spatial arrangements obtained by bending the PHP in the middle of the adiabatic zone with different reciprocal orientations of the evaporator and condenser sections were considered.

Results suggest the minimum heat input required for the PHP start-up increases with the bending angle but does not depend on the reciprocal orientation of the evaporator and the condenser. The maximum heat input, limited by the maximum temperature measured on the surface of the evaporator section, decreases when the bending angle is increased. However, the minimum thermal resistance of the device is not affected significantly by the PHP conformation. Since these results were observed in PHPs fabricated with a low-conductivity material, further work should investigate the performance of PHPs fabricated with flexible materials with higher thermal conductivity than polypropylene, such as doped polymers.

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References
[1] Mameli M, Catarsi A, Mangini D, Pietrasanta L, Michè N, Marengo M, Di Marco P and Filippeschi S 2019, Start-up in microgravity and local thermodynamic states of a hybrid loop thermosyphon/pulsating heat pipe, *Appl. Therm. Eng.* **158** 113771.
[2] Ogata S, Sukegawa E and Kimura T 2014, Lifetime evaluation of ultra-thin polymer pulsating heat pipe, *Proc. IEEE CPMT Symposium*, Japan 15-18.
[3] Oshman C, Li Q, Liew L-A, Yang R, Bright V M and Lee Y C 2013, Flat flexible polymer heat pipes, *J. Micromechanics Microengineering* **23** 015001.
[4] Lim J and Kim S J 2018, Fabrication and experimental evaluation of a polymer-based flexible pulsating heat pipe, *Energy Convers. Manage.* **156** 358–64.
[5] Der O, Marengo M and Bertola V 2018, A low cost, flexible pulsating heat pipe technology, *Proc. 3rd Thermal and Fluids Engineering Conference (TFEC)* no. TFEC-2018-21455.
[6] Der O, Marengo M and Bertola V 2019, Thermal Performance of Pulsating Heat Stripes Built With Plastic Materials, *J. Heat Transfer Trans. ASME* **141** 0918081-8.
[7] Potente H, Karger O and Fiegler G 2002, Laser and microwave welding - the applicability of new process principles, *Macromol. Mater. Eng.* **287**(11) 734–44.
[8] Humbe A, Deshmukh P, Jadhav C and Wadgane S 2014, Review of laser plastic welding process, *International Journal of Research in Engineering Technology* **2**(2) 191-206.
[9] Der O, Edwardson S, Marengo M and Bertola V 2019, Engineered composite polymer sheets with enhanced thermal conductivity, *IOP Conference Series: Materials Science and Engineering* **613** 012008.
[10] Der O, Alqahtani A A, Marengo M and Bertola V 2021, Characterization of polypropylene pulsating heat stripes: Effects of orientation, heat transfer fluid, and loop geometry, *Applied Thermal Engineering* **184** 116304.
[11] Kew P A and Cornwell K 1997, Correlations for the prediction of boiling heat transfer in small-diameter channels, *Appl. Therm. Eng.* **17**(8) 705–15.
[12] Marengo M and Nikolayev V S 2018, Pulsating Heat Pipes: Experimental Analysis, Design and Applications, Encyclopedia of Two-Phase Heat Transfer and Flow IV, ed. J R Thome (London: World Scientific) Vol. 1 Chapter 1, pp. 1–62.
[13] Taft B S, Williams A D and Drolen B L 2012, Review of pulsating heat pipe working fluid selection, *J. Thermophys. Heat Transf.* **26**(4) 651–56.